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Quantification of Uncertainties in the Performance of Smart Composite Stru

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QUANTIFICATION OF UNCERTAINTIES IN THE PERFORMANCES OF SMART COMPOSITE STRUCTURES

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SUMMARY

A composite wing with spars, bulkheads, and built-in control devices is evaluated using a method for the probabilistic assessment of smart composite structures. Structural responses (such as change in angle of attack, vertical displacements, and stresses in regular plies with traditional materials and in control plies with mixed traditional and actuation materials) are probabilistically assessed to quantify their respective scatter. Probabilistic sensitivity factors are computed to identify those parameters that have a significant influence on a specific structural response. Results show that the uncertainties in the responses of smart composite structures can be quantified. Responses such as structural deformation, ply stresses, frequencies, and buckling loads in the presence of defects can be reliably controlled to satisfy specified design requirements.

INTRODUCTION

Aerospace structures are complex assemblages of structural components that operate under severe and often "uncertain" service environments. These types of structures require durability, high reliability, light weight, high performance, and affordable cost. To meet these conflicting requirements, composite materials are the attractive potential candidates. Composite materials possess outstanding mechanical properties with excellent fatigue strength and corrosion resistance. Their mechanical properties are derived from a wide variety of variables such as constituent material properties and laminate characteristics (fiber and void volume ratios, ply orientation, and ply thickness). We know that with current material processing technology these variables are statistical in nature. The current design practice to deal with such uncertainties is to enforce a knockdown or safety factor for each unknown. The advantage of using composite materials for structural design vanishes when using this conventional practice. To exploit the properties of composite materials, a probabilistic assessment of composite structures is needed to quantify the uncertainties of their structural behavior. Only with such an approach can composite structures for a particular purpose be designed based on a chosen acceptable risk while still retaining most of their motivating advantages.

To further enhance the structural performances for new challenges, other advanced concepts should be investigated. Recent developments in smart structure concepts that use actuation materials, such as piezoelectric ceramics, show great potential to enhance structural performances as well as durability and reliability (refs. 1 and 2). Present piezoelectric technology has been successfully applied to small-scale, low-stress structures. However, there are inevitable difficulties when the current technology is applied to large-scale, high-stress composite structures. Such difficulties can be alleviated if special fibers, such as piezoelectric fibers with fast actuation capability, and regular high-strength, high-modulus fibers are used together to form the smart intraply hybrid composites. The control devices in smart structures consist of (1) a polarized material, (2) an electric field parallel to the direction of polarization, and (3) the expansion/contraction effects of the polarized material. When a control voltage is applied, the actuation material expands or contracts so that the structural behavior is altered by a desired amount and its reliability is enhanced. This concept can be readily integrated into a smart composite structure by using combinations of intraply and interply hybrid composites to ascertain if smart composite structures will operate in the design-specified range. At the NASA Lewis Research Center the intraply hybrid mechanics for composites has been embedded in the computer code ICAN (ref. 3) for an integrated composite analysis. In this paper, the uncertainties inherent in all the composite and smart structure parameters are included in the assessment of structural responses by using probabilistic composite structural analysis methods.

SYMBOLS

E_{f11}	fiber modulus in longitudinal direction
E_{f22}	fiber modulus in transverse direction
E_m	matrix elastic modulus
fvr	fiber volume ratio
G_{f12}	in-plane fiber shear modulus
G_{f23}	out-of-plane fiber shear modulus
G_m	matrix shear modulus
stdv	standard deviation
t_{psk}	ply thickness of shell skin
tpst	ply thickness of frames
vvr	void volume ratio
θ_p	ply misalignment
ν_{f12}	in-plane fiber Poisson's ratio
ν_{f23}	out-of-plane fiber Poisson's ratio
ν_m	matrix Poisson's ratio

FUNDAMENTAL CONSIDERATIONS

The smart structure concept, the intraply hybrid composite adaptation, and the computer code IPACS (Integrated Probabilistic Assessment of Composite Structures) are briefly described for completeness.

Smart Structures

A conceptual diagram of a smart composite wing system is depicted in figure 1. The essential parts of a smart composite structure include the following: (1) a composite structure; (2) strategically located sensors; (3) signal processors, which process the signals generated by the sensors; (4) dedicated computers with suitable hardware and software, which continuously check the structural response magnitudes and compare them to predetermined acceptable "red line" values and provide desired corrections to the controller; (5) a controller, which signals the actuators to implement the desired corrections; and (6) actuators.

Intraply Hybrid Adaptation

The adaptation of the intraply hybrid composite concept (ref. 4) to smart composite structures is depicted schematically in figure 2. Figure 2(a) shows the intraply hybrid configuration, and figure 2(b) shows its adaptation to smart composite structures. It can be seen in this figure that the smart composite consists of (1) regular plies, which are made of traditional composite materials, and (2) control plies, which are made of regular strips of traditional composite materials and strips of mixed traditional and actuation materials. Actuators, made of actuation materials such as piezoelectric ceramics or piezoelectric fibers, are used to control the behavior of the composite structure by expanding or contracting the actuation strips to achieve the requisite design and operational goals. However, the strains induced by the actuator are affected by uncertainties in several factors that can only be quantified probabilistically. These include (1) inaccurate measurements made by the sensors, (2) deviation from intended electric field, (3) uncertain actuation strains – resulting from electric field strength relationship, (4) uncertain material properties for the actuation materials, (5) uncertain electric field strength, and (6) improper location of the sensor/control materials. Because of these factors, using control devices increases the uncertainty in an already uncertain composite structural behavior. To properly quantify the benefits of applying the actuation strain, a comprehensive probabilistic assessment is needed to consider all these uncertainties. In this paper, only a few uncertain (random) variables are used for demonstration purposes.

IPACS Computer Code

The IPACS Computer Code (ref. 5) has evolved from extensive research activities at NASA Lewis to develop probabilistic structural analysis methods (ref. 6) and computational composite mechanics (ref. 3). The composite micromechanics, macromechanics, and laminate theory (including interply and intraply hybrids) are embodied in ICAN (ref. 3). IPACS consists of two stand-alone computer modules: PICAN and NESSUS. PICAN is used to simulate

probabilistic composite mechanics (ref. 7). NESSUS uses the information from PICAN to simulate probabilistic structural responses (ref. 8). A block diagram of IPACS is shown in figure 3. Direct coupling of these two modules makes it possible to simulate the uncertainties in all inherent scales of the composite – from constituent materials to the composite structure, including its boundary and loading conditions as well as environmental effects.

The approach for the probabilistic assessment of smart composite structures using IPACS can be described as follows:

(1) Because of the similarity between the thermal strain and the strain induced in the actuation materials, the actuation strains are simulated using thermal strains computed from an uncertain temperature field (representing the electric field strength) and uncertain thermal expansion coefficients (representing the actuation strain coefficients).

(2) The primitive variables are identified at micro and macro levels.

(3) The scatter in the primitive variables, which describe the composite, is represented by specified probability distributions to predict the probabilistic composite behavior.

The primitive variables recognized by the computer code IPACS are (1) fiber and matrix properties at the constituent level, (2) fabrication parameters such as fiber volume ratio, void volume ratio, ply mis-orientation and ply thickness, (3) uncertain loads, temperature/moisture fields, geometry, boundary conditions at the structural level, and (4) uncertain electric field strength and actuation strain coefficient for the control strips.

The first step for the probabilistic assessment of smart composite structures is to identify the uncertain primitive variables at all composite levels as well as the control-related random variables. These variables are then selectively perturbed several times to create a database for the determination of the relationship between the desired structural response (or the desired material property) and the primitive variables. For every given perturbed primitive variable, micromechanics is applied to determine the corresponding perturbed mechanical properties at the ply and laminate level. Laminate theory is then used to determine the perturbed resultant force/moment – strain/curvature relationships. With this relationship at the laminate level, a finite element perturbation analysis is performed to determine the perturbed structural responses corresponding to the selectively perturbed primitive variables. This process is repeated until enough data are generated to enable the appropriate relationship between structural responses and primitive variables to be determined using a computational procedure.

If probabilistic distributions of the primitive variables and a computationally determined relationship between the structural response and the primitive variables are known, fast probability integration (FPI) (ref. 9) is applied. For every discrete response value, a corresponding cumulative probability can be computed very quickly by FPI. This process is repeated until the cumulative distribution function can be appropriately represented. The probabilistic material properties at ply and laminate levels are also computed in the same way as those for the structural responses. The output information from FPI for a given structural response includes the parameters for a special type of probability distribution function and the probabilistic sensitivity factors of the primitive variables to the structural response.

DEMONSTRATION FOR A SMART COMPOSITE WING

The probabilistic assessment of the smart composite structure as described previously is demonstrated by evaluating a smart composite wing. The optimum exact deformed shape of a wing is a function of the particular flight condition. With smart structure concepts, proper deformation change can be obtained from flight condition to flight condition. To achieve these desirable geometries at the required accuracy, the changes have to be inducible within an acceptable range. The feasibility of the desired magnitude of the change and the degree of their expected probabilistic inaccuracies have been studied here with simplification from what a practical system would have to be. The geometry of the composite wing internal structure is shown in figure 4(a). The wing is loaded with nonuniform pressure which varies parabolically from root to tip and from leading edge to trailing edge as shown in figure 4(b). The pressure is assumed to be deterministic in this study while it was assumed to be a random variable in reference 10.

The composite wing is assumed to be made from a graphite-fiber/epoxy-matrix composite. The constituent materials properties, their assumed probabilistic distribution, and the coefficient of variations (representing range of the scatter) are summarized in table I. The composite configurations for the skin, spars, and bulkheads are $[\pm 45/0/90_2/0/\mp 45]_s$, $[0_8]$, and $[0_8]$, respectively. The corresponding fabrication variables used to make the composite wing are summarized in table II. Those for the control are summarized in table III. In each control ply, both control (hybridizing actuation) and traditional strips exist. However, in this paper, the control strip is assigned throughout the control ply for computational simplicity. Also, in each control ply the secondary composite system volume ratio is used to define the percentage of volume for the control device. The percentage of the actuation materials in a secondary composite system is denoted by the control volume ratio. Since actuation materials are much more expensive than traditional materials, the control volume ratio should be determined such that the total cost for a smart composite structure be minimized and subjected to multi-design constraints. Constraints include those typical for traditional composite structural designs and those for actuation materials due to their particular material characteristics such as strain, stress, applied voltage requirements, etc. This consideration will be studied in the future. In this paper, the emphasis is on the demonstration of the probabilistic assessment of smart composite structures using intraply hybrid composites with actuation materials.

The critical structural responses of aircraft wings are, for example, vertical displacements, changes in the angle of attack, natural frequencies, and buckling loads. The results for these responses are now discussed.

Uncertainty in the Vertical Displacement

Two cases are studied for displacement control. One is with 0.5% actuation strain in the 45° plies and the other is with 0.5% actuation strain in both 45° and -45° plies. The scatter in the vertical displacements at mid-span leading and trailing edges is shown in figures 5(a) and (b). Figure 5(a) shows that, by comparing the probability density functions (pdf) between both control cases, the actuation strain in the -45° plies has little effect on the vertical displacement at the

mid-span leading edge. Similarly, in figure 5(b), comparing the pdf for both control cases with that for the case without control shows that the actuation strain in the 45° plies has little effect on the vertical displacement at mid-span trailing edge. However, the actuation strain in the -45° plies provides the major force to lift the mid-span trailing edge for the reduction of the angle of attack. The scatter of the vertical displacement at the tip leading and trailing edges is shown in figures 6(a) and (b). The actuation strain in the 45° and the -45° plies has approximately the same effect on the vertical displacement at the tip leading edge as shown in figure 6(a). However, the actuation strain in the -45° plies significantly decreases the vertical displacement at the tip trailing edge, while the actuation strain in the 45° plies has little effect as shown in figure 6(b).

Uncertainty in the Angle of Attack

The induced vertical displacements deform the wing relative to its support. This induced deformation may include the change in local angle of attack due to twist. The uncertainty in the angle of attack is evaluated as the scatter from a reference position. Results for the scatter in the angle of attack at mid-span are shown in figure 7(a) for a wing with controls. Corresponding results at the tip are shown in figure 8(a). The important observations from these figures are that the angle of attack can be changed substantially with different control configurations: 0.5% actuation strain in the 45° plies versus 0.5% actuation strain in 45° and -45° plies. The collective results in figures 5, 6, 7(a), and 8(a) demonstrate that the intraply hybrid smart composite concept is an effective means for displacement control.

Probabilistic Sensitivity Factors for Uncertainty in the Angle of Attack

The commonly used sensitivity in a deterministic analysis is the performance sensitivity $\partial Z/\partial Xi$, which measures the change in the performance Z due to the change in a design parameter Xi. This concept is extended to the probabilistic analysis to define the probabilistic sensitivity which measures the change in the probability/reliability relative to the change in each random variable. Probabilistic sensitivity factors result from the probabilistic assessment of smart composite structures. These factors provide quantifiable information on which "design parameters" the smart composite structure is most sensitive to. Subsequently, these design parameters can be manufactured, controlled, and adjusted to obtain the "best" benefit with the least change.

The probabilistic sensitivity factors for the angle of attack at mid-span for the case with 0.5% actuation strain applied to the 45° and for the case with 0.5% actuation strain applied to both 45° and -45° plies are shown in figures 7(b) and (c). The probabilistic sensitivity factors for the angle of attack at the tip for both control cases are shown in figures 8(b) and (c). These figures indicate that the control-related parameters (electric field strength, secondary composite system volume ratio, control volume ratio, and control modulus) play the most important roles in the scatter for the angle of attack. Other variables show little contribution to the scatter in this specific study, which may not be true for other problems.

Uncertain Longitudinal Stress

The scatter in the normalized longitudinal ply stresses is shown in figure 9. The control ply for this case is the 45° ply with 0.5% actuation strain. The stresses for the wing without the hole are also shown for comparison. As can be seen, the maximum stress, which is in the 0° ply, can be reduced for a given control arrangement. However, it should be pointed out that the stress in the 45° ply (control ply) increases.

Uncertain Natural Frequencies

Two cases have been studied: The first is with 0.5% actuation strain in the 45° plies, and the second is with 0.5% actuation strain in the 0° plies. Normalized natural frequencies of the first six modes with and without control and with and without a rectangular cutout are shown in figures 10(a) to (f). In figures 10(a) to (d), the actuation strain in the 45° plies has little influence on the first four modes while the actuation strain in the 0° plies has a sizable influence except on the third mode. In figures 10(e) and (f), both actuation strains in the 45° and 0° plies increase the fifth and sixth natural frequencies, but the actuation strain in the 0° plies has more effect. These findings indicate that specific control configuration is needed to control each specific natural frequency and an optimization strategy may be needed to achieve a specific design goal.

Uncertain Buckling Loads

Figure 11 shows the normalized critical buckling loads with and without a rectangular cutout and with and without actuation strain. First buckling loads reduce 10% with a rectangular cutout. When a 0.5% actuation strain is applied to the structure, the first buckling load is further reduced. Therefore, caution is required in exercising the smart structure concept. When one objective is being optimized, other objectives may be penalized. Catastrophic structural failure may occur without warning.

The observation from this assessment is that the natural frequencies and buckling loads can also be controlled by different control configurations to satisfy the specified design criterion. Also, tradeoff studies should be exercised to prevent premature buckling behavior.

GENERAL DISCUSSION

Smart composite structures can be (1) configured through the adaptation of intraply hybrid composites for controls, (2) evaluated by using the equivalence between the thermally and electrically actuation strains, and (3) assessed with probabilistic composite structural analysis to provide a formal and convenient procedure to probabilistically assess their potential in specific structural applications. Smart composite structures will evolve to be effective design concepts in the cost-effective and early utilization of composites in advanced and traditional structural applications because of the in-

service control feature. The procedure described herein provides an efficient way to probabilistically quantify the ranges of uncertainties in various structural responses which dominate the design.

Since the entire system can be simultaneously configured, various tradeoffs can be evaluated to obtain the least-cost/maximum-benefit configurations. The probabilistic sensitivity factors can guide a redesign by manufacturing, controlling, and adjusting the design parameters to obtain the "best" benefit with the least change. These factors can also be used to select the minimum number of experiments required to certify the safe life of specific structural systems and thereby hasten their applications in man-related structures. Also, implementing a smart composite system would require intense further studies and the participation of other disciplines for its proper concurrent engineering realization.

Other major design parameters, which in the past were traded for specific structures, include the power required to provide the controls, its respective generation, and the corresponding weights. The initial and operating costs (life cycle cost) of the entire system must be evaluated for a given risk. This evaluation can be accomplished by structuring formal tailoring methods with multiple objective optimization features. The procedure described herein forms the probabilistic simulation of smart composite structural behavior. This form of analysis is fundamental to any formal tailoring procedure for maximizing the reliability and minimizing the risk.

CONCLUDING REMARKS

A formal procedure is described for the probabilistic assessment of smart composite structures. This procedure includes adapting (1) the intraply hybrid concept for controls, (2) the equivalence between electrical and thermal strains, and (3) the probabilistic composite structural analysis. The important results of applying this procedure to a smart composite wing are the following:

1. The scatter (uncertainty) in the structural deformation (angle of attack and vertical displacements) is probabilistically quantified. The scatter is most sensitive to control-related parameters in this specific case.

2. The mean value of the longitudinal stress in the 45° (control) ply increases as the actuation strain increases. The mean value of the longitudinal stress in the 0° (regular) ply with maximum ply stress decreases with increasing control strain.

3. Natural frequencies and buckling loads can be optimized with different control ratios to satisfy the design and operational requirements.

4. The degree of uncertainty in the structural performance increases with the application of control devices.

5. Caution is required in exercising the smart structure concept. When one objective is being optimized, other objectives may be penalized. Catastrophic structural failure may occur without warning.

Collectively, the results discussed herein indicate that a probabilistic approach is necessary for a realistic assessment of actual conditions; the alternative is extensive and time-consuming testing.

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Table I.—THE STATISTICS OF FIBER AND MATRIX MATERIAL PROPERTIES

Property	Units	Distribution type	Mean	Coefficient of variation
E_{f11}	Msi	Normal	31.0	0.05
E_{f22}	Msi		2.0	
G_{f12}	Msi		2.0	
G_{f23}	Msi		1.0	
v_{f12}	—		0.2	
v_{f23}	—		.25	
E_m	Msi		.5	
G_m	Msi		.185	
v_m	—		.35	

TABLE II.—THE STATISTICS OF FARBIRACTION VARIABLES

Property	Units	Distribution type	Mean	Coefficient of variation
fvr	—	Normal	0.60	0.05
vvr	—		.02	.05
θ_p	deg		.00	.90 (stvd)
t_{psk}	in.		.015	.05
t_{pst}	in.		.080	.05

Table III.—UNCERTAINTIES OF CONTROL-RELATED VARIABLES

Variable	Distribution type	Mean	Coefficient of variation
Secondary composite system volume ratio	Normal	0.50	0.05
Control volume ratio		.60	
Control modulus (Msi)		12.4	
Control strain coefficient (in./V)		$2x10^{-8}$	
Electric field strength (V/in.)		$2.5x10^{5}$	

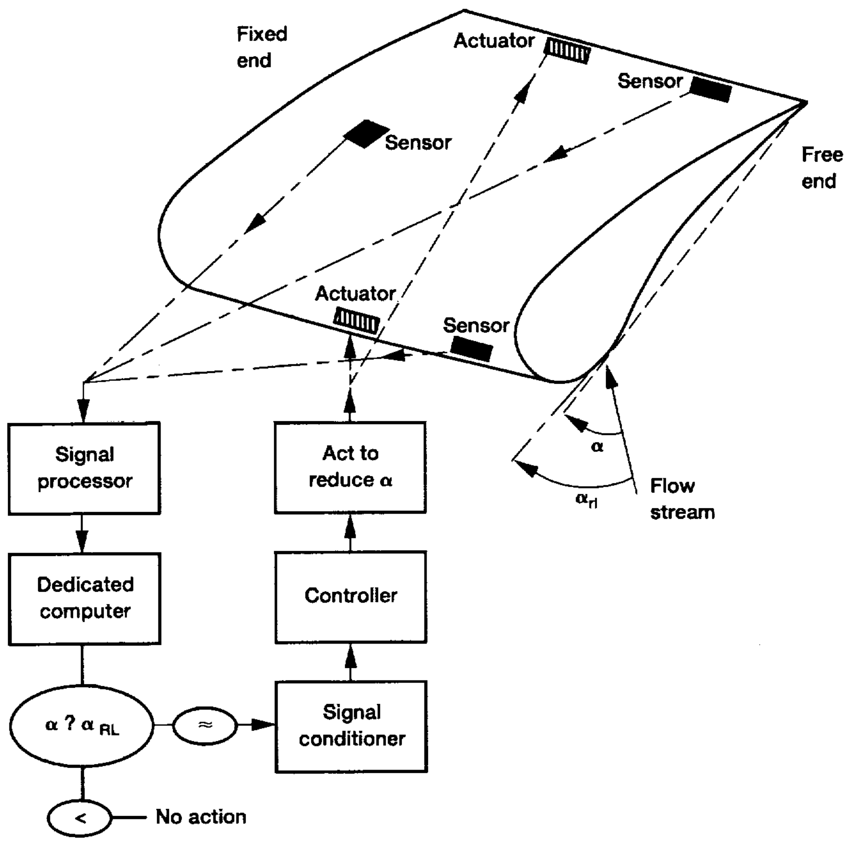
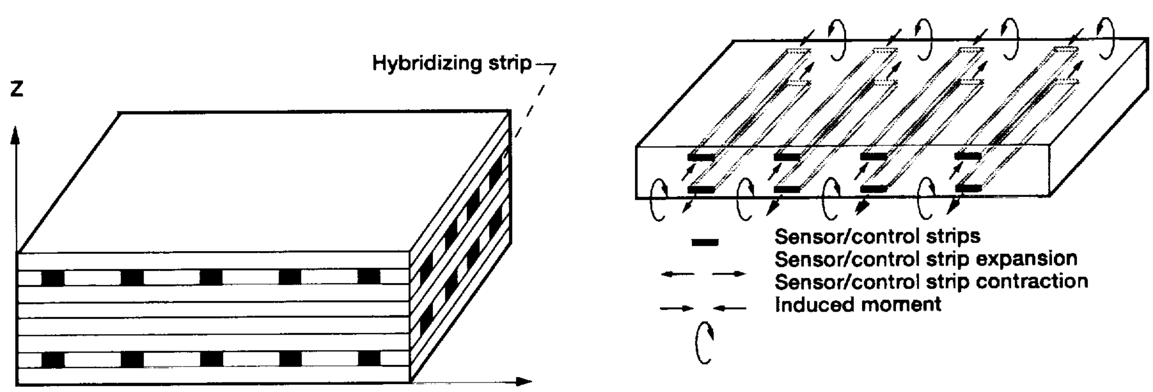


Figure 1.—Conceptual diagram smart composite aircraft wing system.



(a) Intraply Hybrid composite system.

(b) Schematic of structural control using sensor/control materials.

Figure 2.—Adaptation of intraply hybrid to smart composite system.

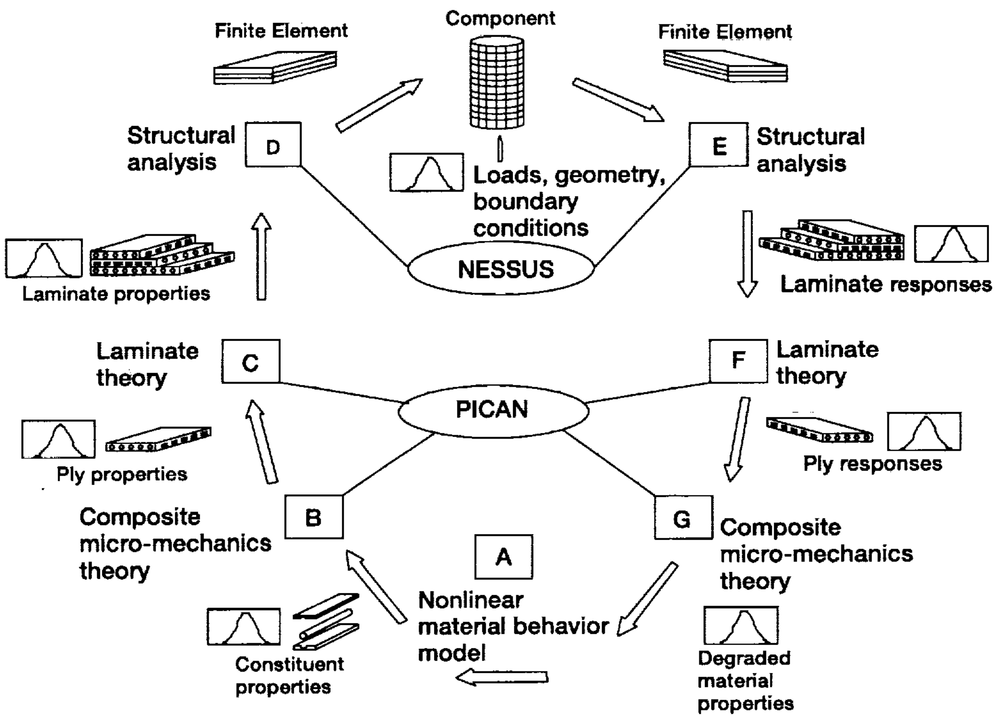
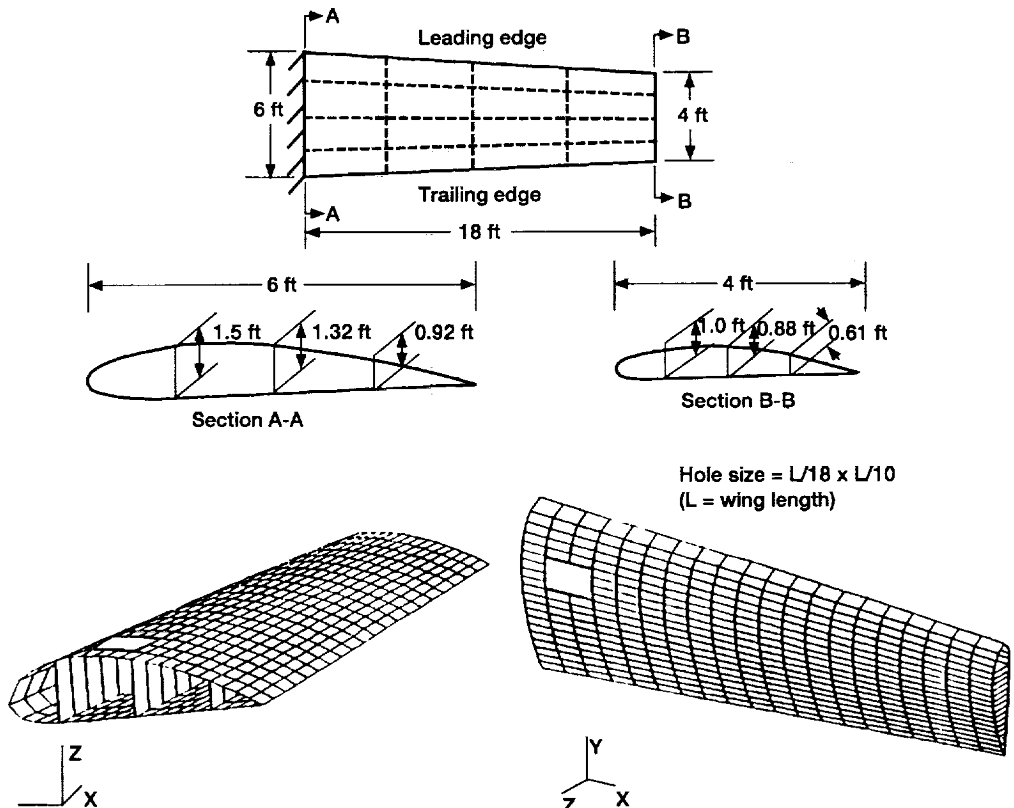
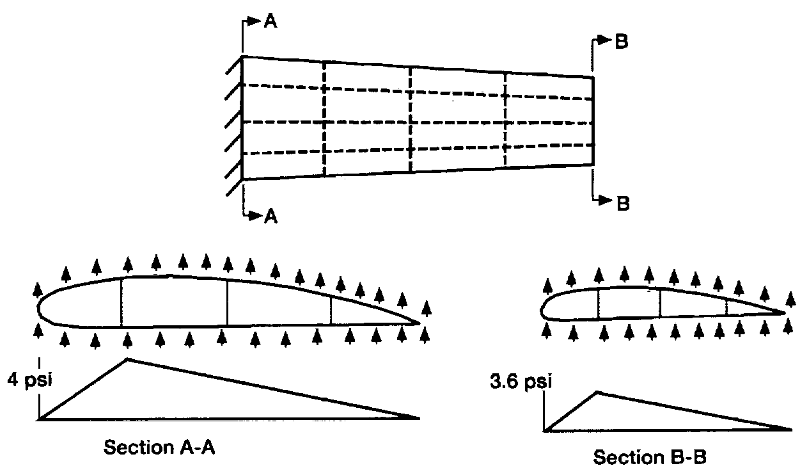


Figure 3.—Schematic of computer code IPACS.

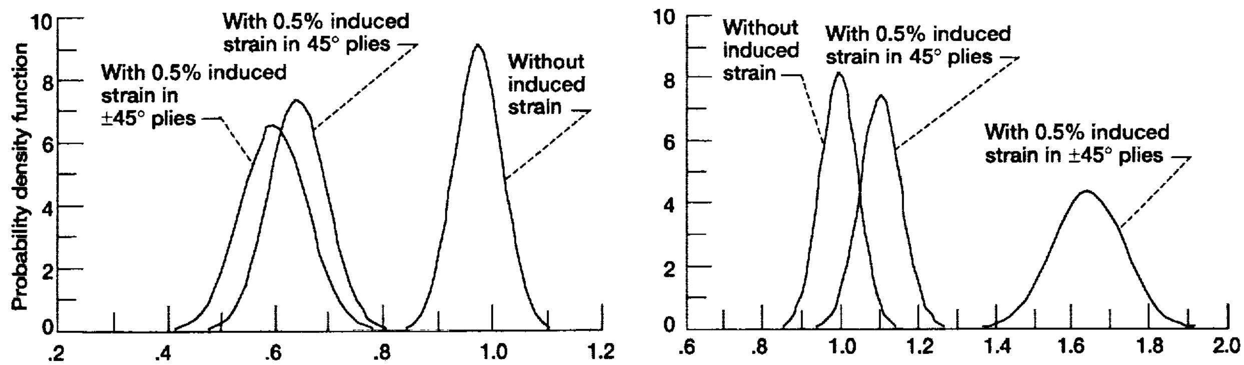


(a) Geometry and finite-element model of composite wing.



(b) Variation of pressure on composite wing.

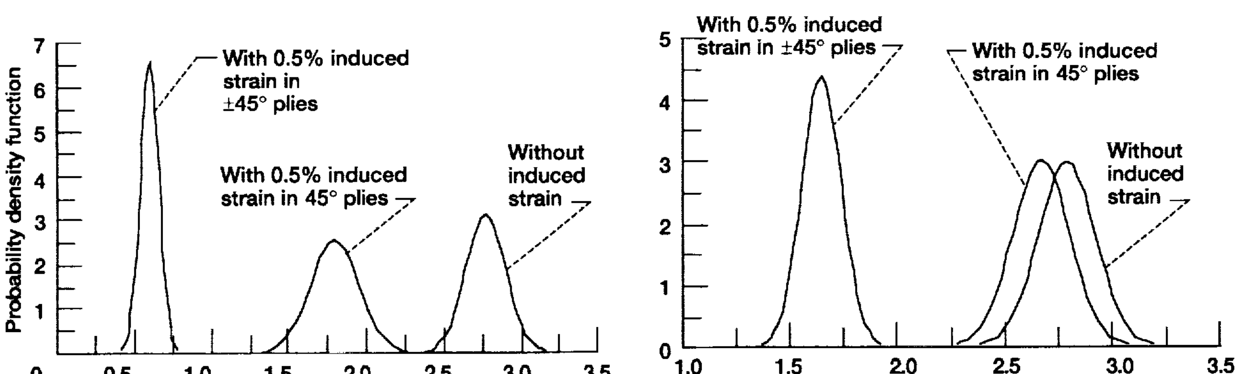
Figure 4.— Smart composite wing.



(a) At leading edge.

(b) At trailing edge.

Figure 5.—Uncertainties — scatter range of vertical displacements at midspan.



(a) At leading edge.

(b) At trailing edge.

Figure 6.—Uncertainties — scatter range of vertical displacements at tip.

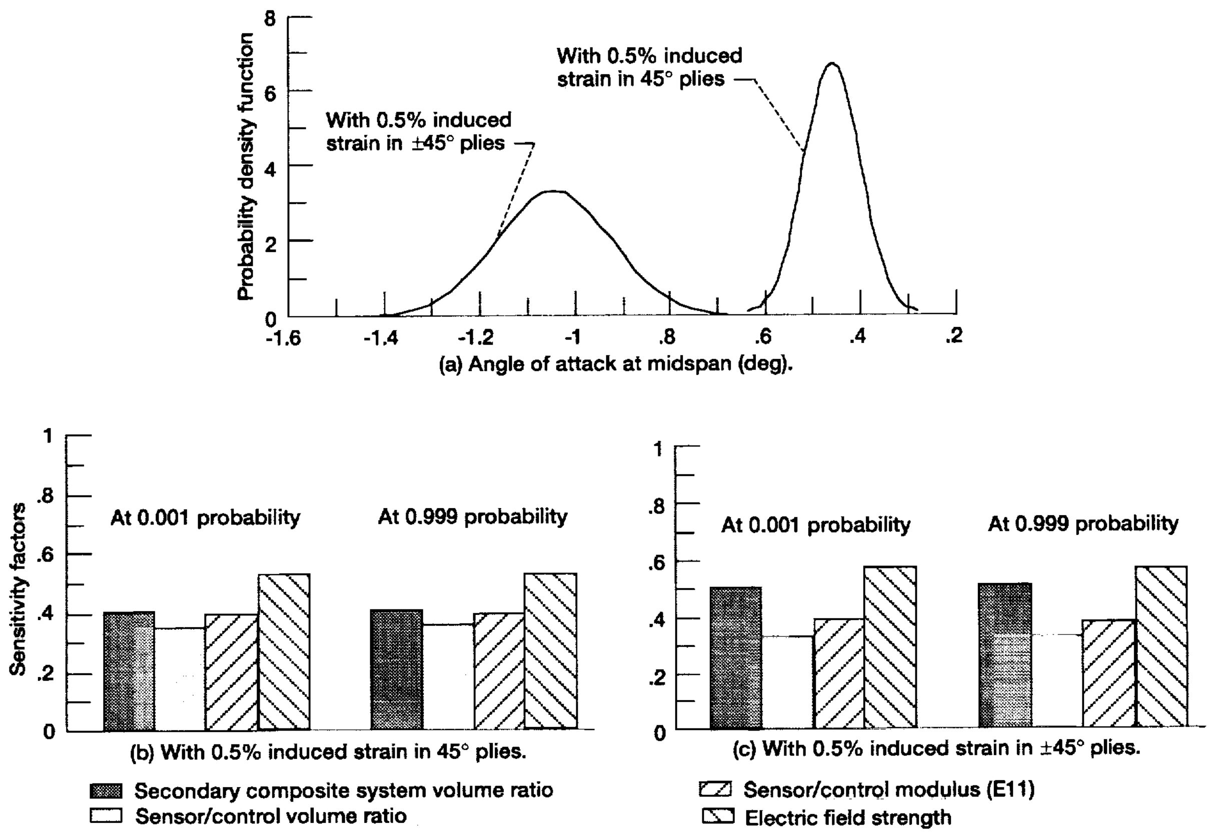


Figure 7.—Angle of attack at midspan, uncertainties — scatter ranges and sensitivities to significant uncertain variables.

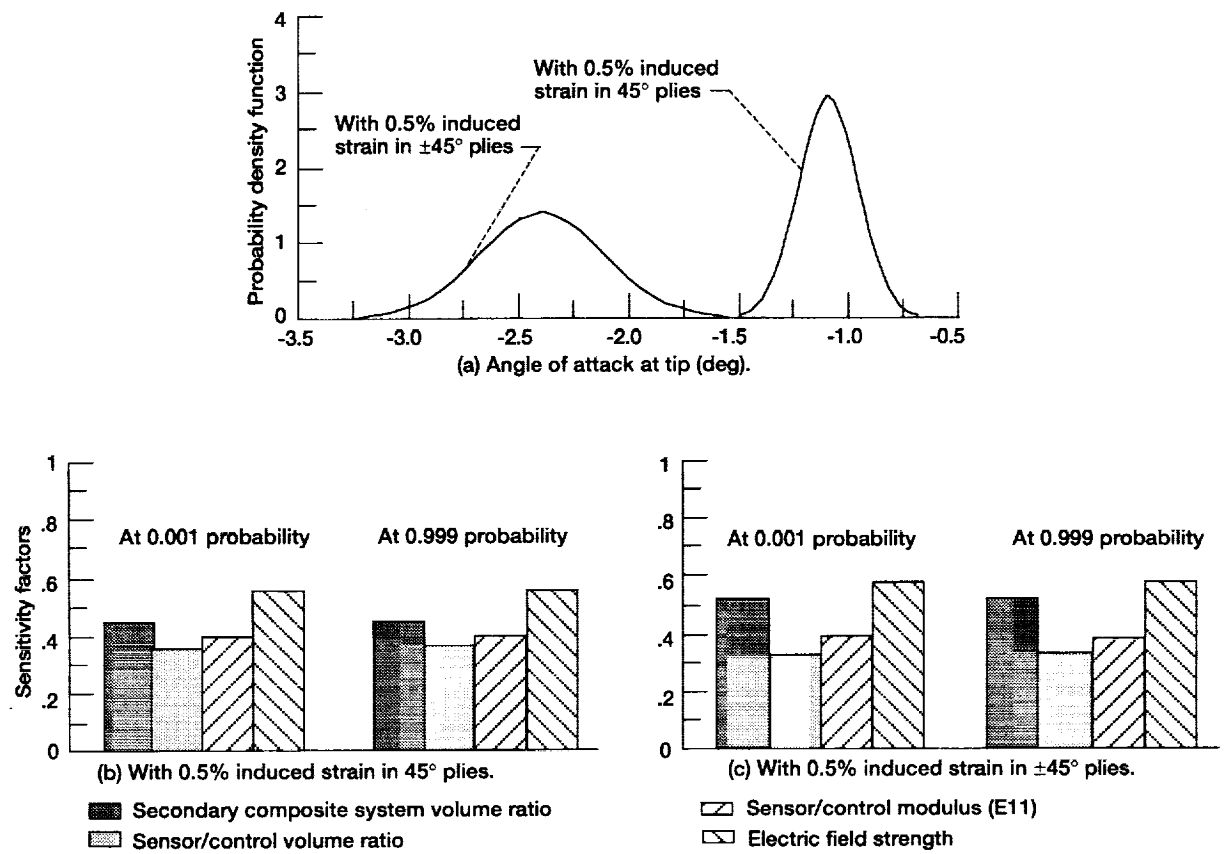


Figure 8.—Angle of attack at tip, uncertainties — scatter ranges an sensitivities to significant uncertain variables.

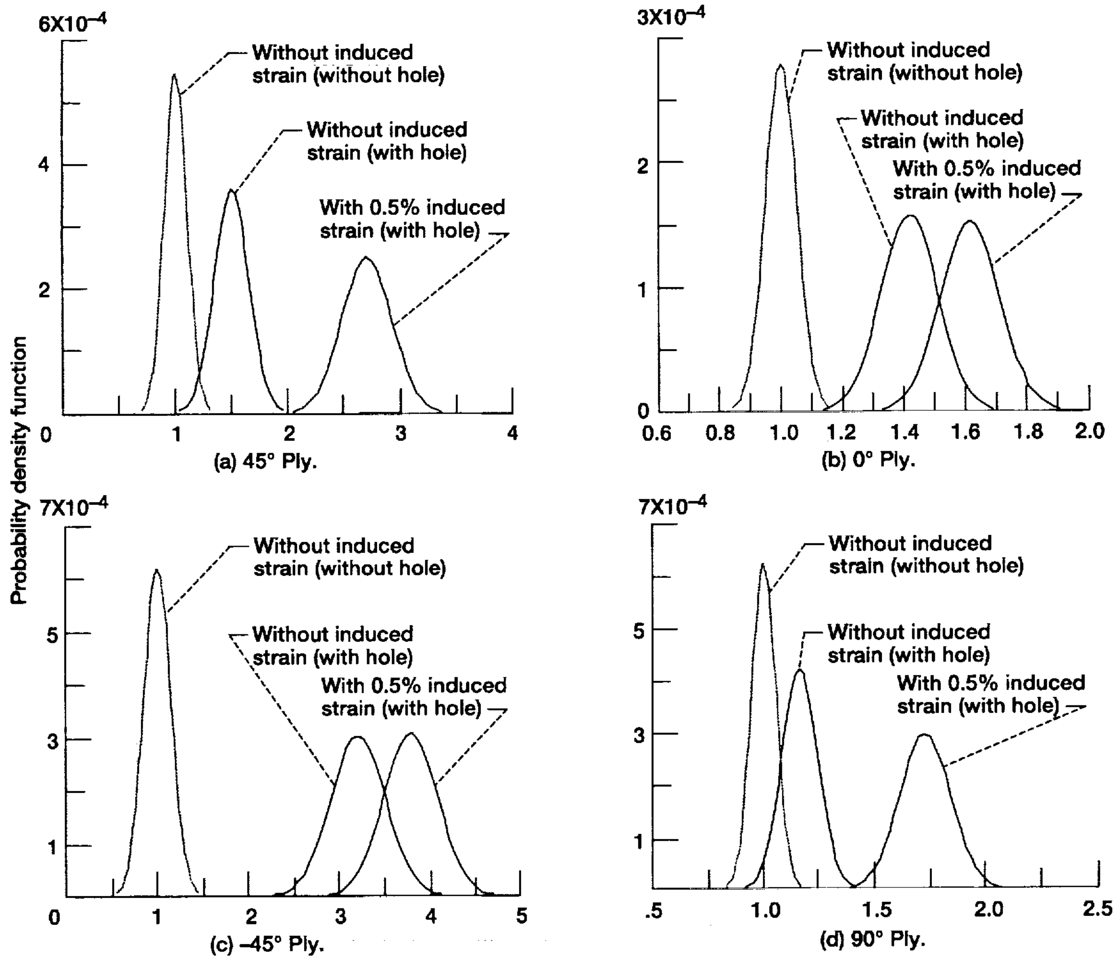


Figure 9.—Normalized longitudinal stress — uncertainties range with/without control in 45° plies.

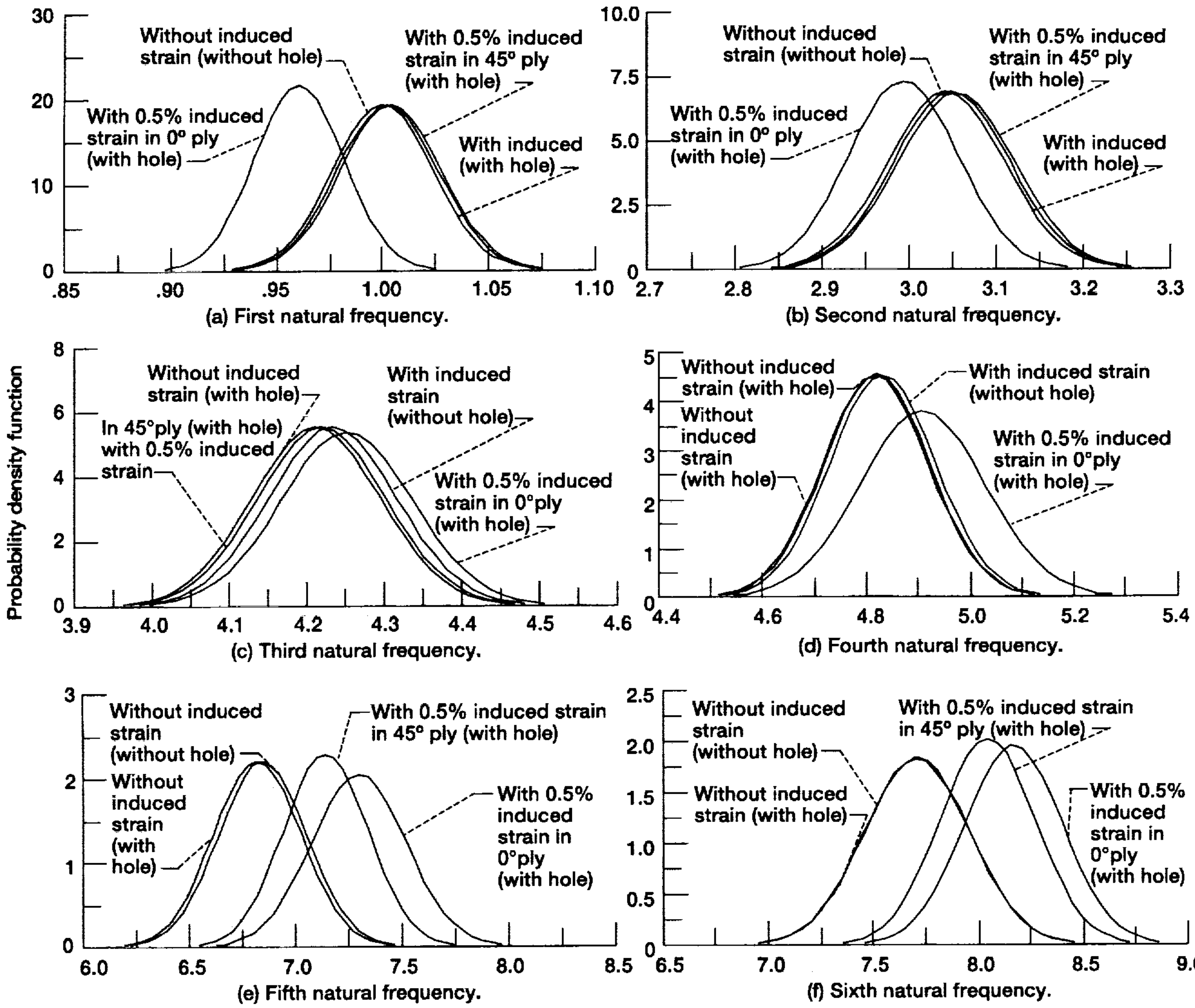


Figure 10.—Normalized natural frequencies, uncertainties — scatter ranges.

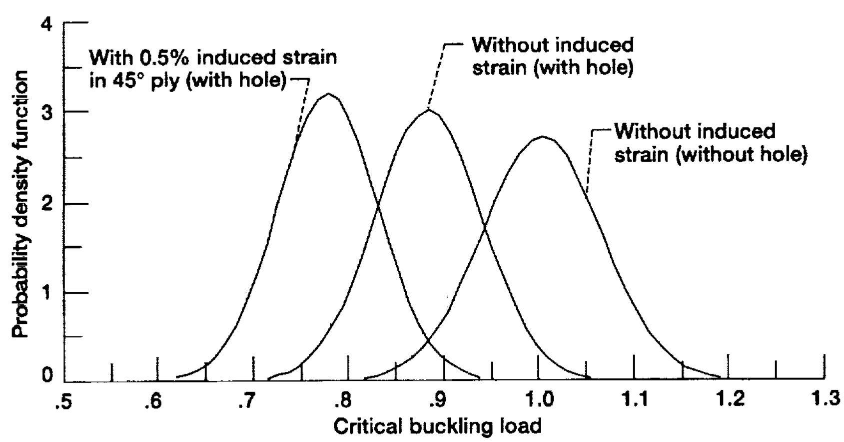


Figure11.—Normalized critical buckling loads, uncertainties — scatter ranges.

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13. ABSTRACT ***(Maximum 200 words)***

A composite wing with spars, bulkheads, and built-in control devices is evaluated using a method for the probabilistic assessment of smart composite structures. Structural responses (such as change in angle of attack, vertical displacements, and stresses in regular plies with traditional materials and in control plies with mixed traditional and actuation materials) are probabilistically assessed to quantify their respective scatter. Probabilistic sensitivity factors are computed to identify those parameters that have a significant influence on a specific structural response. Results show that the uncertainties in the responses of smart composite structures can be quantified. Responses such as structural deformation, ply stresses, frequencies, and buckling loads in the presence of defects can be reliably controlled to satisfy specified design requirements.

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